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LIFE CYCLE MANAGEMENT

Life cycle emissions and energy study of biodiesel derived from waste cooking oil and diesel in Singapore

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Abstract
Background, aim and scope Biodiesel derived from Waste Cooking Oil (WCO) is considered highly environmentally sustainable since WCO is a waste product from domestic and commercial cooking processes and then recycled to a transportation fuel in Singapore. In addition, it avoids the conversion of land use for crop production. This is a strong advantage for Singapore which has relatively smaller land space than other countries. The import of virgin oil as feedstock into Singapore is also avoided. Therefore, the more appropriate feedstock to produce biodiesel in Singapore context is WCO. According to the National Environment Agency, diesel vehicles in Singapore contribute 50% of the total particulate matter smaller than 2.5 µm ($PM_{0.25}$) emissions to air ambient. Hence, the aim of this life cycle assessment study was to compare the environmental performances of biodiesel derived from WCO and low sulphur diesel in terms of global warming potential, life cycle energy efficiency (LCEE) and fossil energy ratio (FER) using the life cycle inventory. The results of this study would serve as a reference for energy policy makers and environmental agencies.
Materials and methods ISO14040 and ISO14044 (ISO14040 2006; ISO 14044 2006) are used as the method for implementing this study. This comparative study between biodiesel derived from WCO and low sulphur diesel is done by comparing the life cycle inventory results. The tailpipe emission tests were done using a gas analyser.
Results Biodiesel production data are collected from a local facility. The production of main ingredients, types of transportation, conversion of WCO to biodiesel and the usage of biodiesel were considered within the dataset. Production of low sulphur diesel was modelled according to several references. The phases include foreign crude oil production, refining, transporting of diesel to station and finally the usage of diesel. The testing vehicle for both transportation fuels is an ISUZU pickup truck with engine capacity of 3,059 cc and in direct injection combustion chamber type. The functional unit in this study is output of 1 transportation-km.
Discussion In this section, two types of emissions are discussed. First is the net life cycle emission. The second is the exhaust tailpipe emissions. Highest amount of reduction on a life cycle basis is $PM_{2.5}$ and PM_{10} with a significant reduction of 99.99%. On the exhaust tailpipe emission basis, the reduction for total particulate matter is 94.80%. The LCEE of biodiesel produced from WCO is calculated as 86.93%. This is higher than biodiesel reported from US studies (using soybean as feedstock) which is 80.55%. The low LCEE value of 71.09% for low sulphur diesel could be attributed by the fact that Singapore depends greatly on foreign crude oil production and imports. The FER is calculated to be 9.39. The life cycle of biodiesel produced from the recycling of WCO produces more than nine times as much energy in its final fuel product as it uses in fossil energy. This is three times higher than biodiesel derived from soya oil in the USA.
Conclusions The emission results and the life cycle energy efficiencies have indicated that the replacement of low sulphur diesel with biodiesel derived from WCO as a transportation fuel is favourable.

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Recommendations and perspectives In Singapore, the potential substitution percentage of diesel by biodiesel if all of the WCO can be collected and processed to biodiesel is 1.42%. There is a need for recyclers to convince the food establishments and users of cooking oil of the benefits of recycling cooking oil, which in turn obtains a steady source of WCO as feedstock for biodiesel production. In addition, as the biodiesel life cycle defined is very much dependent on WCO as a feedstock, it is recommended to optimise the WCO collection network.

Keywords Biodiesel · Life cycle assessment · LCA · Life cycle management · LCM · Recycling · Singapore · Waste cooking oil

1 Background, aim and scope

Biodiesel production has increased worldwide. Many life cycle assessment (LCA) studies regarding biodiesel have been done in the USA (NREL 1998) and Europe (IES 2006; L-B-Systemtechnik GMbH 2002). In Asia, cases of biodiesel produced from Waste Cooking Oil (WCO) are found in Thailand (Pleanjai et al. 2009), Philippines (Pascual and Tan 2004), Hong Kong (Leung 2001), etc. Biodiesel derived from WCO is considered to be more environmentally sustainable since it is a waste product and recycled as transportation fuel in Singapore. In addition, it avoids the conversion of land use for crop production. This is a strong advantage for Singapore which has limited land space. The import of virgin oil as feedstock into Singapore is also avoided. Therefore, the more appropriate feedstock to produce biodiesel in Singapore context is WCO.

Since the quantity of WCO generated is not available, the percentage of WCO is estimated from Japan and Thailand figures where the food culture is similar to Singapore. It is thus estimated that approximately 18.5% of the cooking oil consumption can be recovered as WCO in Singapore. In 2007, 107,087 tons of cooking oil is consumed. (AVA 2007) Assuming that the consumption pattern does not change much, the calculated potential amount of WCO that can be recovered is 20,000 tons per year. In Singapore, water waste from residential and industrial area will be discharged into the public sewage system. However, there is some discharge of wastewater into open drains, canals and rivers, but are regulated by Environmental Protection and Management Act and the Environmental Protection and Management (Trade Effluent) Regulations (NEA Water Pollution 2008). The WCO discharge will contribute to eutrophication as it has high concentration of chemical oxygen demand (COD). The average COD concentration of WCO collected by the industrial partner is approximated as 0.07 kg COD per kilogram WCO. There is also a high cost to treat the wastewater which is polluted with WCO in the sewage system. Therefore, there is a need to recycle WCO without an additional load on the environment.

In Singapore, the current recycling rate of WCO is 0.25% (assuming industrial partner is a major WCO collector in Singapore). The low recycling rate indicates that the majority amount of WCO has been discharged to the sewage system annually. Using the WCO collection data from industrial partner, the projected annual WCO collected is 49.592 tons. The projected annual WCO discharged is therefore 19,950 tons.

On top of the lack of WCO recycling issue in Singapore, understanding the overall energy requirements of both biodiesel and diesel in the Singapore context is also important. Energy efficiency helps us to determine how much additional energy must be used to convert the energy available in raw materials used in the fuel's life cycle to a useful transportation fuel. As the depletion of non-renewable sources continues, it is therefore important to know the biodiesel and diesel dependency degree on non-renewable sources. This can be known by calculating the energy renewability which is discussed later.

The National Environment Agency (NEA) uses The United States Environmental Protection Agency standard to assess Singapore's ambient air quality (USEPA 2009). This is in an effort to protect public health. The main air pollutants in Singapore are due mainly to transportation; thus, one solution is to source for cleaner transportation fuel in order to reduce pollution (NEA 2009).

Pollutants such as carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), oxides of nitrogen (NO_x) and particulate matter (PM) can cause significant human health effects in localised area. Sulphur dioxide (SO_2) is also regulated for ambient air quality. According to the NEA and the Land Transport and Authority (LTA), diesel vehicles in the country contribute 50% of the total $PM_{2.5}$ emissions (particulate matter smaller than 2.5 μm) (NEA 2005). Therefore, we need to assess the levels of improvements of the air pollutants if we switch to biodiesel. In addition, the 'Singapore Green Plan 2012' initiative aims at reducing carbon dioxide (CO_2) emissions in 2012 by a minimum of 25.0% of 1990 levels (MEWR 2006).

The objective of this LCA study was therefore to compare biodiesel and diesel from the environmental perspectives of global warming potential, air pollution and energy efficiencies. This study will provide as a reference for energy policy makers and environmental agencies.

2 Materials and methods

2.1 Goal and scope definition

The goal of this study was to compare the environmental impacts mainly in terms of global warming potential, air pollution and energy efficiency of both biodiesel and diesel. For a fair and consistent comparison, a functional unit is required. The functional unit represents a quantitative measure of the output of a system. In this study, the functional unit is 1 transportation-km in order to take these factors into account: engine mechanical efficiencies, type of fuel and emissions from combustion.

In this study, the greenhouse gas emissions that are considered are CO_2, CH_4, N_2O, VOC, NMVOC, etc. The other air pollutant emissions are CO, NO_x, PM and SO_2. Two types of energy efficiencies are also reported. One is life cycle energy efficiency. The definitions and equation are as shown below:

$$\mathrm{LCEE} = FPE/TPE \tag{1}$$

where LCEE represents the life cycle energy efficiency, FPE represents the fuel product energy and TPE represents the total primary energy.

LCEE is the measure of the amount of energy that goes into a fuel cycle that actually ends up in the fuel product. FPE is the energy contained in the final fuel product. TPE is the cumulative energy content of all resources extracted from the environment.

One of the subsets of the primary energy inputs is the feedstock energy. It is energy contained in raw materials that end up directly in the final fuel product. The next subset of primary energy is process energy. It is the energy required for the processing of feedstock energy into its final fuel product form. Process energy consists primarily of coal, natural gas, oil and other power sources consumed directly or indirectly in the fuel's life cycle.

The second energy efficiency type is the fossil energy ratio. The definitions and equation are as shown below:

$$\mathrm{FER} = FPE/FE \tag{2}$$

where FER represents the fossil energy ratio, FPE represents the fuel product energy and FE represents the fossil energy.

FER is the degree of renewability of the fuel. FPE is the energy contained in the final fuel product. FE is the primary energy that comes from fossil sources specifically (coal, oil and natural gas).

The higher the FER, the less dependent it is on fossil fuel. When the FER is >1, the fuel begins to take advantage of the fossil energy required in making the fuel ready to be used for transportation purposes. As a fuel approaches being completely renewable, its fossil energy ratio approaches "infinity".

2.2 System boundary

The scope of the LCA study includes the system boundary depicted in Fig. 1 for biodiesel. The study site of biodiesel production is in the western part of Singapore. The system boundary encompasses the following processes and networks:

- Methanol (for transesterification reaction) and potassium hydroxide (catalyst) production (production is assumed to take place at the suppliers' sites)
- Transport of methanol and potassium hydroxide to biodiesel production site (due to lack of upstream information, assumptions of the transportation fuel and distances were made)
- Transport of WCO to biodiesel production site using biodiesel as transport fuel
- Conversion of WCO to biodiesel
- Transport of biodiesel to customer sites using biodiesel as transport fuel
- Biodiesel usage

The main ingredients in this LCA study are methanol, potassium hydroxide and WCO. WCO is collected within Singapore via a collection network. The average collection distance (travelled to point of collection) of the WCO collection network is 29 km. The points of collection are mainly restaurants and are scattered all over Singapore. On average, for every 1 km travelled, 8 kg of WCO can be collected. As methanol and potassium hydroxide production are outside of alpha biofuels' operations, secondary data are used instead. Methanol is sourced from a company where its manufacturing activity is in Malaysia whilst potassium hydroxide from South Korea. The source of methanol data is GABI software, but its emission data are modified by calculating the energy requirement and converting it to Malaysia electricity grid equivalent. The potassium hydroxide data are modelled based on mass and energy balance and then converted to Korea's electricity grid equivalent. The electricity grid information of the respective countries are compiled according to several references and then calculated (Jafar et al. 2008; MEC 2007; Lee et al. 2004). We believe that this is a more realistic approach as opposed to using generic data because the overall emission data of the same product tend to be different regionally.

The allocation was done based on the mass output of biodiesel (setting to 1 kg of biodiesel) and glycerin. The

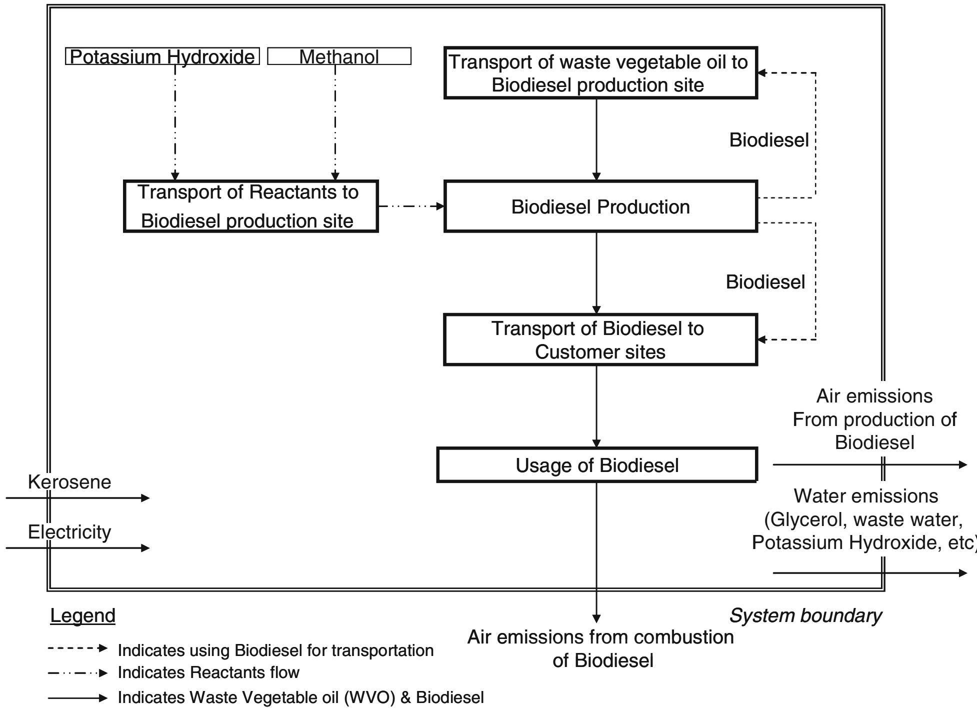

Fig. 1 System boundary of WCO recycling

allocation shows that approximately 1.005 kg of WCO, 0.180 kg of methanol and 0.015 kg of potassium hydroxide are required to produce 1 kg of biodiesel. For every 1 kg of biodiesel, 0.143 kg of glycerin is produced. Most of the biodiesel production data are primary data and therefore are process- and facility-specific to our industrial partner. The production of biodiesel starts with the pretreatment of WCO. The purpose of the pretreatment process is to preheat WCO and remove any waste residue. The amount of water in WCO sludge is very much subjective to the origin of the collection source. The water content in WCO sludge is <30% most of the times. The waste residues are mainly made up of sludge. Examples include remains of food residue such as meat, chicken skin, etc. No chemicals are added during the pretreatment process. The production of biodiesel is via a transesterification reaction. Excess methanol is supplied to ensure complete transesterification reaction. Unreacted methanol is recycled as a feed stream. Purification of biodiesel is done via a dry washing process to remove residues of methanol and potassium hydroxide. The Singapore electricity grid is modelled according to the proportion of energy sources: 80% natural gas and 20% oil (IEA 2006). The data from the clean development mechanism project is also used within the dataset (NCCC 2009). However, due to data difficulties, only major global warming potential gases are considered within the dataset. The fossil fuel consumption data are also taken into consideration for energy analysis (Kannan et al. 2004a, b, c).

Biodiesel is distributed via a network and the average distribution distance is calculated as (travelled to point of distribution) 27 km. Finally, the exhaust emission for usage of biodiesel is measured. The testing vehicle is an ISUZU pickup truck with engine capacity of 3,059 cc and in direct injection combustion chamber type. The emission tests were conducted at SETSCO in Singapore and measured using the same testing vehicle. The reference flows of biodiesel and diesel are 17.6 and 15.4 kg/100 km, respectively.

Crude oil is extracted in the Middle East countries (Saudi Arabia, Qatar, United Arab Emirates and Bahrain) and Southeast Asia (Vietnam and Malaysia) and imported into Singapore for refining. The refinery products include naphtha, liquified petroleum gases, motor gasoline, aviation gasoline, jet kerosene, residual fuel oil and diesel. There are three refineries in Singapore. They are Exxon Mobil's in Jurong/Pulau Ayer Chawan, Royal Dutch Shell's Pulau Bukom and Singapore Petroleum Company's Pulau Merlimau (EIA 2006).

Due to difficulties in obtaining the data, the LCI of diesel is modelled according to several references. Mass allocation was used to allocate diesel and the co-products. The emission results of diesel during the usage phase are obtained from the same vehicle which used biodiesel. Before testing, flushing was done to ensure that there are no residues of biodiesel.

2.3 Impact assessment and interpretation

The characterisation model of global warming potential (GWP) used is the model developed by Intergovernmental Panel on Climate Change (IPCC). The characterisation factors are based on 100-year time horizon for each

greenhouse gas to the air (IPCC 2006). The unit of the $GWP_{100\ years}$ is kilogram CO_2-equivalent.

3 Results and discussions

3.1 Emissions

In this section, two types of emissions are discussed. One is the net life cycle emissions. The second one is the exhaust tailpipe emissions. The exhaust tailpipe emissions are measured because they are localised emissions to the air during the transportation fuel usage phase, which will contribute directly to the air ambient and have a direct impact on the public health in Singapore. Thus, they are presented separately.

In Table 1, the highest amount of reduction on a life cycle basis is total $PM_{2.5}$ and PM_{10} with a significant reduction of 99.99%. SO_2 has a similar amount of reduction with 99.99%. As shown in Table 2, the total $PM_{2.5}$ and PM_{10} as well as SO_2 on the localised tailpipe emissions basis are 94.80% and 83.02%. The next highest life cycle reduction is NO_x with 97.95%. However, in the tailpipe emissions in Table 2, there is a higher amount of NO_x for biodiesel than diesel. The slight increase of NO_x has been noted in many studies, but the reason is unknown. Fuel oxygen content is believed to be the main reason because PM and soot are effective heat radiators, and when they are mostly oxidised by oxygen, the temperature inside the cylinder may increase and result in higher NO_x. In this study, the amount of increase is 3.02%. Thus, the overall improvement of total PM, SO_2, NO_x and N_2O when diesel is replaced with biodiesel are more significant from the life cycle perspective.

The next highest life cycle reductions are CO with 90.54% and NMVOC with 91.52%. In the tailpipe emissions in Table 2, it exhibits the same directions but of different magnitudes. The CO and NMVOC tailpipe emissions are 20.36% and 52.93%, respectively. The difference in the tailpipe emissions could be due to the different fuel oxygen content. Biodiesel has higher oxygen content than diesel; thus, lesser oxygen is needed for combustion reaction. As a result, the tendency for more complete combustion is increased and hence the CO and NMVOC reduction. For CH_4, the reduction is 83.36%. From the life cycle perspectives, the refinery processes could have contributed mostly to the reductions. The CH_4 reduction is more significant on the life cycle basis.

It is as shown in Table 2 that there is a higher amount of CO_2 in the tailpipe emissions with about 2.94%. However, about 95% of the CO_2 in the tailpipe emissions is biogenic and is recycled from WCO, and only approximately 5% is fossil-based, which comes from methanol. From the overall life cycle perspectives, there is a significant amount of fossil fuel CO_2 reduction.

Following the emission results is the impact assessment. Biogenic CO_2 is not taken into account for impact assessment. The calculated GWP100 years for diesel and biodiesel are 1.08 and 0.006 kg CO_2-equivalent per kilometre, respectively. The percentage contributions of life cycle GHG emission of biodiesel is as shown in Fig. 2. The percentage contribution of the usage phase contributes 48.4%. The percentages of collection and distribution network are approximately 1.1% and 0%, respectively. This can mean that the current distribution network is more efficient than the collection network. This is expected because the collection network is based on fixed collection locations, and thus, it is more difficult to collect than to distribute. In addition, 9.0% and 12.5% are contributed by production and transportation of methanol and potassium hydroxide, respectively. The total percentage contribution by the ingredients is therefore 21.5%. Last but not least, the percentage contribution of the Singapore electricity grid is 29.0%.

3.2 Energy efficiencies

The LCEE of biodiesel produced from WCO is calculated as 87%. This is higher than reported from US studies (using soybean as feedstock) which is 80.555%. (NREL 1998) The low LCEE value of 71% for diesel could be attributed by the fact that Singapore depends greatly on foreign crude

Table 1 Net life cycle emissions

Net life cycle emissions (kg/km)	Diesel	Biodiesel	Percentage change
Net life cycle SO_2	5.01E−01	3.43E−05	−99.99
Net life cycle NO_x	7.99E−02	1.64E−03	−97.95
Net life cycle N_2O	9.02E−06	3.53E−07	−96.08
Net life cycle fossil fuel CO_2	9.41E−01	4.31E−02	−95.42
Net life cycle CO	2.02E−02	1.91E−03	−90.54
Total $PM_{2.5}$ and PM_{10}	1.42E−01	1.35E−05	−99.99
Net life cycle NMVOC	7.23E−03	6.13E−04	−91.52
Net life cycle CH_4	4.28E−03	7.58E−04	−82.28

Table 2 Tailpipe emissions during usage

Tailpipe emissions (kg/km)	Diesel	Biodiesel	Percentage (%) change
SO_2	1.90E−04	3.22E−05	−83.02
NO_x	1.98E−03	2.04E−03	3.02
CO_2	5.61E−01	5.77E−01	2.94
CO	2.99E−03	2.38E−03	−20.36
Total $PM_{2.5}$ and PM_{10}	2.04E−04	1.06E−05	−94.80
NMVOC	1.60E−03	7.53E−04	−52.93
CH_4	7.90E−04	7.86E−04	−0.52

oil production and imports. The farther the refinery site, the longer the tanker needs to travel and thus requires more energy for transportation.

The fossil energy ratio is then calculated to be 9.4. The life cycle of biodiesel produced from the recycling of WCO produces more than nine times as much energy in its final fuel product as it uses in fossil energy. This is three times higher than biodiesel derived from soya oil in the USA (NREL 1998). The higher indication of renewability means that using WCO to produce biodiesel is actually more leveraging on fossil energy than soya bean oil does. The high fossil energy ratio for biodiesel indicates that biodiesel derived from WCO is renewable and is not dependent on fossil energy. One megajoule of biodiesel uses 1.15 MJ of TPE, and out of 1.15 MJ of TPE, only 0.11 MJ comes from fossil fuel. The rest comes from the WCO. Biodiesel is therefore heavily dependent on WCO for its primary energy since about 90% of the total primary energy is contributed by WCO. However, the current recycling rate of WCO is only 0.25%. This means that there is still a potential amount of 19,950 tons of uncollected WCO from domestic household and other restaurants. In addition, there is a lack of main WCO collection points over the island. Because the availability of WCO as a feedstock is important for biodiesel production, the collection network has to be improved. One suggestion is to set up a WCO collection centre for easy collection. The level of improvement for the substitution of the collection network by a WCO collection centre is, however, not discussed further in this paper. On the other hand, FER of 0.74 for diesel indicates its low renewability. This is anticipated because it is highly dependent on crude oil as a raw material (Table 3).

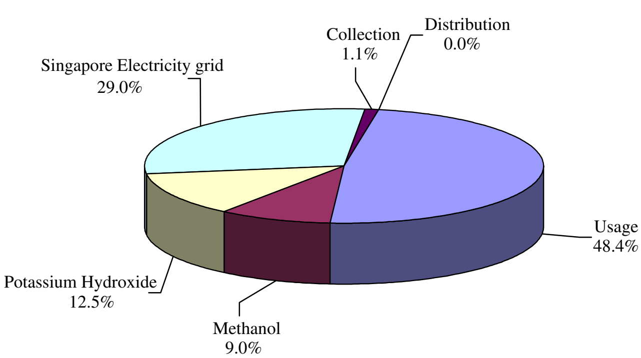

Fig. 2 Percentage contribution of respective process and ingredients to overall fossil fuel carbon emissions for biodiesel

4 Conclusions

This paper has modelled the life cycle processes of manufacturing biodiesel from collection of WCO from food establishments to usage in transport in Singapore. The environmental impacts of the life cycle is quantified and compared against the use of conventional ultra-low sulphur diesel. The results have shown that it is more environmentally beneficial collecting waste cooking oil, processing it into biodiesel and using in transportation. The emission results and the life cycle energy efficiencies have indicated that the replacement of low sulphur diesel with biodiesel derived from WCO as a transportation fuel is favourable.

5 Recommendations and perspectives

If all the WCO of about 20,000 tons is collected to produce biodiesel, biodiesel production can amount to as much as 19,900 tons per year. In 2006, 1.4 million tons of diesel is consumed in Singapore (IEA 2006). Assuming that the diesel consumption pattern does not change a lot, the potential substitution percentage of diesel by biodiesel is approximately 1.42%. Although the amount is not significant, it serves in replacing partial non-renewable fuel demand by renewable fuel. In addition, there are the avoided economic and environmental impacts of WCO disposal in the sewage system. As recycling of WCO proves to be beneficial to the environment, the manufac-

Table 3 Energy efficiencies

Energy efficiencies	Diesel	Biodiesel
LCEE (%)	71.09	86.93
FER	0.74	9.39

turers have to convince the food establishments and users of cooking oil of the benefits and help to obtain a steady source of WCO as feedstock for biodiesel production.

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